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ORIGINAL PAPER

The geography of social vulnerability and wildfire occurrence (1984–2018) in the conterminous USA

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Abstract
Wildfire is increasing in frequency, extent, and severity in many parts of the USA. Considering the unequal burden of natural hazards on socially vulnerable populations, we ask here, how are characteristics of social vulnerability associated with wildfire occurrence nationwide, at different scales and across differing levels of wildland–urban interface development? To answer this question, we first identify all non-urban census tracts in the USA that have experienced a wildfire since 1984. Using 26 different measures of social vulnerability, we compare these tracts to non-urban census tracts that have not experienced a wildfire. In doing so, we identify notable social vulnerabilities in areas that have experienced wildfire, including higher unemployment, higher employment in extractive industries, higher percentage of people living in mobile homes, higher percentages of Native Americans, higher percentage of people with less than 12th grade education, and higher populations of people with special needs. Breaking our data into eight regions and comparing tracts with a high proportion of wildland–urban interface (WUI) to those with a low proportion of WUI, we find that these characteristics are generally consistent across regions of the USA and vary slightly between high WUI and low WUI tracts. Overall, we find a robust pattern of higher social vulnerability in areas with wildfire occurrence. Whereas previous studies about social vulnerability to wildfire focus on relationships with wildfire hazard potential or concentrate on a single region, this study fills a knowledge gap by examining the relationship between social vulnerability and wildfire occurrence nationwide.

Keywords Social vulnerability indicators · Wildland–urban interface · Census data · Rural geographies · Environmental justice

1 Introduction

In recent decades, the USA has experienced increased wildfire activity and growing losses—including fatalities, housing and infrastructure destroyed, and ecological damage—as a result of changes in both land use and climate (Williams et al. 2019).

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Development within the wildland–urban interface (WUI), that area where housing and wildland vegetation combine (Radeloff et al. 2005, 2018), has increased the extent and number of housing units at risk to wildfire. The WUI forms a focal area where homes and lives are threatened by wildfire because ignitions are often human caused, and there is ample vegetation to serve as fuel once wildfires are ignited (Nagy et al. 2018; Balch et al. 2017). Climatic conditions in some regions have proven increasingly advantageous to wildfire spread, particularly after extended droughts or during high wind events (Abatzoglou et al. 2018), although these complex relationships vary in strength and nature geographically (Littell et al. 2016; Keeley and Syphard 2016). Combined, these forces have led many to acknowledge that it is increasingly important to "live with fire" in ways that minimize risk to human lives and properties, while maintaining wildfire as a vital ecological process (Fischer et al. 2016; Moritz et al. 2014; Steelman 2016).

Despite the need to coexist with wildfire, our understanding of the demographic characteristics of people most frequently experiencing fire remains less developed than our knowledge of the biophysical conditions most conducive to fire behavior and risk (Thomas et al. 2022). Moreover, understanding populations' social vulnerability, or susceptibility to harm, is a critical part of anticipating and redressing the effects of wildfire and natural hazards, more broadly (Schumann et al. 2020). Social vulnerability is manifest when inequities, structural racism, and historical disadvantages interact with individuals' characteristics, such as wealth, education, race, or age, thus limiting the capacities of these individuals, their households, and communities to undertake disaster preparation, mitigation, evacuation, and recovery efforts (Pulido 2000; Cutter et al. 2003; Blaikie et al. 2014; Highfield et al. 2014). Understanding social vulnerability is particularly important for wildfire, a hazard uniquely tied to human presence (Syphard et al. 2017; Bowman et al. 2011), given that people cause the majority of wildfire ignitions (Balch et al. 2013; Keeley and Syphard 2018), influence vegetation conditions and fire regimes (Bowman et al. 2011; Spies et al. 2014), and can play a critical role in reducing sensitivity through house- and landscape-level mitigation activities (Paveglio et al. 2019). Although the majority of buildings destroyed by wildfire nationally are found in the WUI (Kramer et al. 2018; Caggiano et al. 2020), rural areas also experience significant wildfire losses (Kramer et al. 2018; Syphard et al. 2019). Additionally, wildfires extend across diverse regions of the USA, including the West and Great Plains, but also in the Southeast and areas of the Upper Midwest. Considering this diversity of environments, it is possible that social vulnerability characteristics may vary with wildfire exposure, between regions, and/or across a range of development densities.

Studies to date suggest inconsistent relationships between different facets of social vulnerability, WUI, wildfire risk, and exposure. On one hand, WUI areas are sometimes described as areas of relative economic advantage, where residents are incentivized by fire suppression practices to locate near natural amenities and live in higher value or newer homes (Collins and Kearns 2008; Poudyal et al. 2012; Simon and Dooling 2013). On the other hand, issues of housing availability and affordability are often characterized as a key factor leading to WUI growth, thus placing some of the most vulnerable people at risk of wildfire (Thomas et al. 2022; Chase and Hansen 2021). Many of these studies have examined wildfire risk (i.e., biophysical likelihood of wildfire) and have used different study areas (regional or national extent, some including urban areas, other focused on rural areas) (Table 1). However, rural and WUI communities can be diverse, with a variety of social, economic, and housing characteristics found even within a single community (Edgeley and Paveglio 2017).

Table 1 Summary of peer-reviewed studies on the association between social vulnerability and wildfire

Study	Measure of wildfire risk/exposure	Measure of social vulnerability	Study area	Scale of analysis	Rural/WUI housing focus?	Uses multi-year data?	Finding: Is fire associated with higher social vulnerability?
Ojerio et al. (2011)	Risk (potential)	9 variables: socioeconomic, demographic and special needs	State: Arizona	Block group	No	No	No
Pouydal et al. (2012)	Risk (potential)	5 variables: economic, housing and race/ethnicity	Region: US Southeast	Block group	No	No	No
Wigtil et al. (2016)	Risk (potential)	SoVI	Nation	Block group	Yes: WUI and non-WUI	No	No
Grala et al. (2017)	Wildfire occurrence (human-caused only)	4 variables: economic and population density	State: Mississippi	County	No	Yes: 1991–2005	Yes
Davies et al. (2018)	Risk (potential)	13 variables: adaptive capacity	Nation	Tract	No	No	No
Andersen and Sugg (2019)	Risk (potential) incorporating wildfire occurrence data	SoVI	Substate: Western North Carolina	Tract	No	Yes: 1985–2016	No
Palaiologou et al. (2019)	Risk (potential)	21 variables: socioeconomic and demographic, similar to SoVI	Substate: Locations in Washington, California and Oregon	Block group	No	No	No
Gabbe et al. (2020)	Risk (potential)	Centers for Disease Control Social Vulnerability Index (SVI) and state-specific subsidized housing data	State: California	Tract	Yes: WUI and non-WUI	No	Yes

Table 1 (continued)

Study	Measure of wildfire risk/exposure	Measure of social vulnerability	Study area	Scale of analysis	Rural/WUI housing focus?	Uses multi-year data?	Finding: Is fire associated with higher social vulnerability?
Masri et al. (2021)	Wildfire occurrence (frequency and percent burned area)	17 variables: economic, housing, demographic and information access	State: California	Tract	Yes: Urban and rural	Yes: 2000–2020	Yes
Wibbenmayer and Robertson (2022)	Risk (potential)	4 variables: economic and demographic	Region: US West	Parcel with block group and tract data	No	No	No

Accordingly, our study investigates the relationship between wildfire occurrence and social vulnerability at the tract level across WUI and rural areas, thus changing the frame of reference and broadening our understanding of human sensitivity to wildfire. This study explores which individual social vulnerability characteristics ($n = 26$), guided by the Social Vulnerability Index (SoVI) framework (Cutter et al. 2003), coincide spatially with wildfire. For the ease of comparison, we grouped these characteristics into six pillars: employment, housing, population structure, race/ethnicity, socioeconomic status, and special needs populations (e.g., Emrich et al. 2022; Rufat et al. 2019). Specifically, we ask three questions:

1. Nationally, do social vulnerability characteristics differ between areas with and without wildfire occurrence?
2. Are these differences in social vulnerability characteristics consistent across regions?
3. Are these differences in social vulnerability characteristics consistent for non-urban census tracts containing low proportions of WUI (i.e., rural areas) and high proportions of WUI?

This investigation moves us beyond the question of "who *could* experience wildfire?" toward "who *has* experienced wildfire?" and invites re-examination of popular narratives about wildfire risk and privilege, in both high WUI and low WUI (i.e., more rural) areas. By examining wildfire occurrence across a range of housing densities, from more rural to primarily WUI housing, we hope to further examine how inequities in wildfire exposure unfold across the landscape. Using a real measure of wildfire occurrence and many different aspects of SoVI will allow new insights into social vulnerability and adaptation opportunities at a time when wildfire risk and inequities in mitigation assistance are both increasingly apparent (Anderson et al. 2023; Lambrou et al. 2023).

2 Background

As wildfire losses have increased in the USA, there are a growing number of efforts to examine wildfire vulnerability in order to target prevention measures like fuel treatments and infrastructure hardening. Many of these efforts are extensions of wildfire risk assessments, where the likelihood and intensity of wildfire in a particular place is simulated through modeling techniques and then extended to consider exposure (e.g., Ager et al. 2011, 2012; Johnston et al. 2020). Wildfire hazard potential (WHP) data (Dillon and Gilbertson-Day 2020), which quantify the relative potential for extreme fire behavior, are useful in assessing relationships between wildfire likelihood and biophysical exposure. However, most wildfire risk assessments either neglect to consider conditions that may amplify social vulnerability or include them only superficially in loss estimation (Johnston et al. 2020).

2.1 Previous wildfire vulnerability research that considers social vulnerability

Given the need for greater sophistication in treating human dimensions of wildfire risk, recent studies have begun to analyze social vulnerability and adaptive capacity using detailed demographic data at different scales, across a range of study areas, and using a variety of biophysical data. Table 1 identifies and compares key studies from the USA that explore the spatial relationships between social vulnerability and wildfire. For simplicity,

we only include studies that focus directly on the fire hazard, rather than the secondary hazard of wildfire smoke, which is more diffuse. Of the ten studies identified, seven consider future wildfire risk/potential (i.e., they address the question of "who *could* experience wildfire?"), two consider previous wildfire occurrence (i.e., "who *has* experienced wildfire?"), and one study blends the two types of measures.

The studies of wildfire risk (potential) have yielded similar conclusions (Table 1): nationally and across the West, wildfire risk is generally not associated with higher social vulnerability, although given the extent and diversity of the conterminous US in both biophysical hazards and social characteristics, there are some locations where WUI and/or fire hazards do combine with social vulnerability (Wigtil et al. 2016; Davies et al. 2018; Wibbenmayer and Robertson 2022). Similarly, in the Southeastern US wildfire risk was negatively associated with social vulnerability, although there were some states and locations in the region where the two coincided (Pouydal et al. 2012). A statewide analysis in California found that WUI areas tend to be more affluent than non-WUI areas (urban and rural, combined), but the analysis also identified areas where housing subsidies and WUI areas overlapped as well as concentration of manufactured housing in the WUI (Gabbe et al. 2020). A regional study identified block groups in north-central Washington and northern New Mexico where higher social vulnerability and risk of wildfire transmission from public lands overlapped (Palaiologou et al. 2019).

The few studies that examine previous wildfire exposure and population characteristics show more varied patterns (Table 1), and importantly, none is conducted on a nationwide scale. A couple of these studies have found that socially vulnerable populations are more likely to experience wildfire. For example, in the state of Mississippi, wildfire occurrence (1991–2005) at the county-level was highly correlated with poverty (Grala et al. 2017), and in California, census tracts with more wildfire activity (2000–2020) tended to have older populations, higher proportions of low-income residents, lower median household incomes, lower home values, and higher populations of Native Americans (Masri et al. 2021). Despite these positive associations with some social vulnerability indicators, other indicators were not associated with wildfire. For example, census tracts with more wildfire activity had lower populations of racial and ethnic minorities, other than Native Americans, and more affluent census tracts in California had higher proportions of area burned (Masri et al. 2021). In western North Carolina, 85% of all wildfires from 1985 to 2016 occurred in census tracts with low to moderate social vulnerability (Andersen and Sugg 2019).

These inconsistent findings reflect the range of study areas and scales used to investigate wildfire and social vulnerability, the myriad ways that wildfire risk, exposure, and outcomes can be considered, and the diversity of WUI areas themselves (Table 1). For example, examinations of historical wildfire patterns and social characteristics are typically undertaken at state or regional levels, while national assessments of hazards rely on risk measures (e.g., simulations of likelihood and intensity of wildfires) as opposed to previous patterns of exposure (Cutter et al. 2016). Researchers have also depicted social vulnerability in different ways (e.g., composite indicators vs. individual variables) over varying units of analysis, including parcels, census block groups, tracts, and counties. Finally, choosing appropriate sample universes for wildfire exposure is challenging—urban areas are sometimes included in these studies, especially those examining wildfire smoke exposure (Johnson Gaither et al. 2011; Afrin and Garcia-Menendez 2021; Rappold et al. 2017), although actual likelihood of losing homes to wildfire in urban areas is relatively low (Kramer et al. 2018). Ultimately, how the study universe is defined has implications for the findings—cast a net too wide with coarse data, and researchers may essentially compare urban and rural

places or may not examine finer-scale variation in social vulnerability (e.g., across regions, within states, or within counties). When the density and type of development is explicitly considered, studies use a range of methods, relying upon tract level classifications (e.g., rural–urban commuting codes) or prevalence of WUI housing.

2.2 Social vulnerability and wildfire occurrence in the present study

The present study is a first attempt to examine how local patterns of wildfire exposure align with social vulnerability characteristics across the entire conterminous USA. Our approach is informed by established hazards theory, which conceptualizes place vulnerability as a combination of exposure and sensitivity, both social and ecological (Cutter 1996; Emrich and Cutter 2011). In the case of wildfire, there are multiple reasons why wildfire occurrence and losses may be heightened in communities with higher social vulnerability: ignitions linked to cigarette smoking, older and lower quality homes more likely to be damaged in fire, fewer resources for fire preparedness, response and mitigation, and less government capacity in general. We acknowledge as well that wildfire impacts, post-fire outcomes (e.g., rebuilding, repopulation, risk reduction), and broader adaptive changes in the human and ecological environments gradually alter place vulnerability before the next wildfire (Schumann et al. 2020). However, given the exploratory nature of this study, we focus solely on demographic data (not ecological conditions), and we make no claims about *why* social vulnerability characteristics differ between areas with and without wildfire occurrence. Given the timing of our demographic data and span of wildfire events we consider (see more below in methods), it is outside the scope of this study to consider how wildfire events, and indeed successive wildfire events, might be further changing social characteristics of resident populations. We note, however, that due to worsening trends in wildfire extent and intensity as well as the realities of vegetation succession and regrowth, those places that have already experienced wildfire are likely to experience wildfire again (Radeloff et al. 2018; McWethy et al. 2019).

3 Methods

In this study, we used a systematic approach to examine national and regional variation in social vulnerability characteristics across non-urban areas in relation to wildfire occurrence. We also examined nationwide variation in social vulnerability characteristics with respect to the proportion of housing located in the WUI. Our study area was the conterminous USA (Fig. 1), and we used US Department of Agriculture (USDA) Forest Service assessment regions to examine regional variation (Oswalt et al 2019). Our unit of observation was the census tract (2010 boundaries), the smallest spatial unit at which subcounty demographic data from the American Community Survey (ACS) generally exists with at least moderate reliability nationwide. [See National Research Council (2007) and Spielman et al. (2014) for further discussion of data reliability thresholds]. For our analysis we excluded all census tracts located entirely within the urban core based on the ESRI USA Urban Areas (ESRI 2018). Urban areas are contiguous blocks or block groups with a total population of at least 50,000, where at least one unit contains a minimum density of 1000 people per square mile and adjacent units contain at least 500 people per square mile (ESRI 2018). These urban areas make up about 50% of all census tracts but contained no wildfires prior to and including 2018, according to the Monitoring Trends in Burn Severity

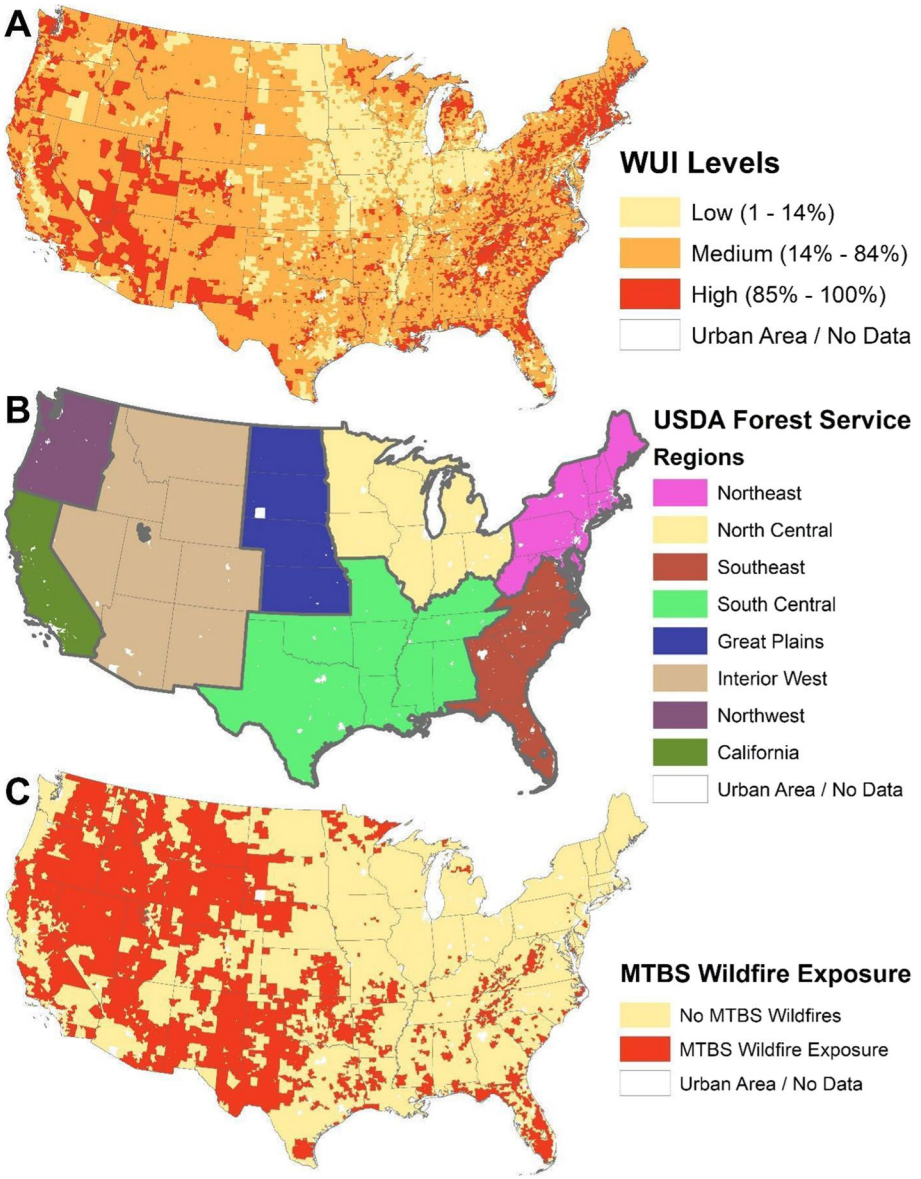

Fig. 1 **A** US Census tracts by WUI levels, **B** USDA Forest Service regions used for analysis, **C** US Census tracts by past wildfire occurrence

(MTBS) Dataset (U.S. Geological Survey 2019). For the remaining non-urban census tracts, we noted the presence or absence of wildfire from 1984 to 2018 recorded in the MTBS by overlaying wildfire perimeters and census tract boundaries. The MTBS database provides fire perimeters for all fires in the USA that are at least 500 acres (202 ha) in the eastern USA and at least 1000 acres (405 ha) in the western USA. MTBS identifies a total of 13,572 wildfire events from 1984 to 2018 with the median fire event occurring in

2004. Wildfire perimeters are mapped via remote sensing using 30 m data from Landsat satellites.

3.1 Social vulnerability variables and WUI classification

The selection of social vulnerability variables was guided by the Social Vulnerability Index (SoVI® 2006–2010) framework, first developed by the University of South Carolina's Hazards and Vulnerability Research Institute. The variables were generated from US Census 5-Year ACS data (2006–2010) and were gathered from the University of Central Florida's Vulnerability Mapping and Analysis Platform. This dataset includes a suite ($n = 29$) of socioeconomic and socio-demographic variables (HVRI 2015), which past research suggests influences individual or community capacity to prepare for, respond to, and recover from hazards (Emrich and Cutter 2011). Among various approaches to measure social vulnerability, the Social Vulnerability Index (SoVI) (Cutter et al. 2003) is a widely adopted method to estimate and map vulnerable and marginalized communities in the USA across various natural hazards (Davies et al 2018; Rufat et al. 2015; Yu et al. 2020). Recognizing mixed results from previous studies of composite indices of social vulnerability and wildfire at various geographies, we examine individual inputs to SoVI and wildfire. This approach enables us to test differences in univariate social vulnerability variables between areas with and without wildfire exposure to uncover more specific links between the drivers of social vulnerability that may manifest differently across a landscape. We eliminated two variables (median gross rent and mean house value) from our analysis because they were highly correlated with the wealth variable (Percent of people earning more than $200,000). We also eliminated a third variable (hospitals per capita) because, at the tract level of analysis, these data are not available. Therefore, 26 variables comprise our analysis and provide information on distinct dimensions of social vulnerability (Table 2). To aid interpretation of results, we grouped these 26 variables into six theoretical pillars based on previous social vulnerability validation studies (Rufat et al. 2019; Emrich 2005): employment, housing, population structure, race and ethnicity, socioeconomic status, and populations with special needs. Similar to Masri et al. (2021), we used only one ACS dataset (from a single time period) to avoid challenges with census definitions for social characteristics and census geographies that tend to change over time. Selection of 5-Year ACS data (2006–2010) enabled us to capture social vulnerability characteristics based on a moving average near the midpoint of our wildfire dataset (median fire event in 2004) and coincident with available mapped WUI data from 2010.

Mapped WUI data for the year 2010 were obtained from the Silvis laboratory (Radeloff and Helmers 2018). This dataset follows definitions in the Federal Register (2001) to combine housing densities at the census block level with wildland vegetation to determine where housing (density of 1 home per 40 acres or more) is found in close proximity to or intermixed with wildland vegetation (Radeloff et al. 2018). WUI data for 2010 were the only data available at the time of our analyses and are an apt choice for the study not only because they are near the midpoint of our wildfire data, but because WUI growth was relatively slow from 2010 to 2020, in the aftermath of the 2008 recession (Radeloff et al. 2023). Using this dataset, we summed housing totals by WUI status for each census tract, and classified census tracts by proportion of housing in WUI. Tracts were "low WUI" if they were in the bottom third of all census tracts in terms of percent of housing in WUI. This low WUI class had a maximum percent WUI housing of 14%. Given that we excluded urban tracts from our study area, these low WUI tracts contained mostly rural or lower density housing. We classified tracts as high WUI

Table 2 Definitions and summary statistics for social vulnerability variables

Social vulnerability pillar	Variable	Mean	Std. dev
Employment structure	Percent civilian unemployment	0.25	0.10
	Percent employment in extractive industries	0.04	0.06
	Percent employment in service industry	0.18	0.07
	Percent female participation in labor force	0.47	0.07
Housing	Percent renters	0.24	0.15
	Percent mobile homes	0.10	0.13
	Percent unoccupied housing units	0.14	0.12
Population structure	Percent population under 5 years or 65 and over	0.22	0.07
	Percent of children living in 2-parent families	0.70	0.19
	Median age	40.73	8.42
	Percent female	0.50	0.07
	Percent female-headed households	0.11	0.07
	People per unit	2.59	0.49
Race/ethnicity	Percent Asian	0.02	0.05
	Percent Black	0.09	0.16
	Percent Hispanic	0.10	0.16
	Percent Native American	0.01	0.06
Socioeconomic status	Percent poverty	0.14	0.10
	Percent households earning over $200,000 annually	0.05	0.07
	Per capita income	$28,022.36	$13,729.89
	Percent with less than 12th grade education	0.12	0.09
Special needs	Percent households receiving social security benefits	0.34	0.11
	Percent speaking English as a second language with limited English proficiency	0.15	0.16
	Nursing home residents per capita	0.01	0.01
	Percent of population without health insurance	0.11	0.07
	Percent of housing units with no car	0.06	0.06

if they were in the top third in terms of percent WUI housing. These "high WUI" tracts had a minimum percent WUI housing of 85%. For our analysis of low and high WUI tracts, we excluded all tracts that fell in the middle third of the distribution to ensure that our comparison captured differences between the lower and upper parts of the distribution.

Once compiled, our dataset consisted of 2253 "wildfire" tracts that experienced a fire from 1984 to 2018, including 152 low WUI (i.e., rural) and 816 high WUI tracts, which represented roughly 6% of all non-urban census tracts in the USA (Table 3). Both low WUI and high WUI wildfire tracts were dispersed throughout the conterminous USA. The remaining non-urban tracts that did not experience wildfire were deemed "non-wildfire tracts" ($n = 35{,}220$).

3.2 Do social vulnerability characteristics differ between areas with and without wildfire occurrence?

Identifying those social vulnerability characteristics that occurred with wildfire exposure required application of independent sample t-tests between tracts that experienced

Table 3 Number of census tracts with and without wildfire in low, medium, and high WUI tracts

	Census tracts with wildfire	Census tracts without wildfire	Area (sq km.) of census tracts and (Std. Dev in parentheses)
Low WUI census tracts (0–14% housing in WUI)	152	12,341	112.40 (390.05)
Medium WUI census tracts (14–85% housing in WUI)	1285	11,204	397.30 (1201.50)
High WUI census tracts (85–100% housing in WUI)	816	11,675	119.3985 (537.68)

wildfire ($n = 2253$) and tracts that did not ($n = 35{,}220$) for all 26 variables. For each social vulnerability variable, we calculated the difference between the mean values for wildfire and non-wildfire tracts and tested for statistical significance. To help make these differences easier to understand, we also calculated the percent differences in means between wildfire and non-wildfire tracts. All t-tests assumed unequal variances for each social vulnerability variable. All statistical tests were performed using STATA version 17.0.

3.3 Are these differences in social vulnerability characteristics between burned and unburned areas consistent across regions?

Identifying whether differences in social vulnerability found nationwide are consistent across regions required an additional set of comparisons. Using the same methods implemented in the nationwide analysis, we ran t-tests assuming unequal variances on the means of social vulnerability characteristics for wildfire and non-wildfire tracts separately for eight regions (Table 4). For the regional analysis, we used eight regions from the USDA Forest Service's assessment work in support of the Resources Planning Act (Oswalt et al. 2019) (Fig. 1). We compared these results to the nationwide results and to each other. For each characteristic we asked how many regions agreed with the nationwide trend (in sign and statistical significance) and how many differed.

Table 4 Number of census tracts with and without wildfire in each USDA Forest Service assessment region

	Census tracts with wildfire	Census tracts without wildfire
Northeast	55	6865
North central	55	7275
Southeast	435	6064
South central	715	8061
Great Plains	135	1061
Interior West	493	2290
Northwest	139	1121
California	226	2483

3.4 Are these differences in social vulnerability characteristics between burned and unburned areas consistent for low WUI and high WUI census tracts?

Identifying whether relationships between wildfire exposure and social vulnerability characteristics differ between low WUI and high WUI census tracts required the data be divided into low and high WUI tracts and then analyzed in the same manner as for each dataset above. We compared the sign and significance of the mean differences between wildfire and non-wildfire tracts for each WUI group. There were far fewer tracts that had experienced wildfire than those that had not (Table 3). Accordingly, independent sample t-tests that accounted for unequal variances were used throughout.

3.5 Robustness checks

Concern that the comparison of all non-urban census tracts might be misleading if some census tracts had little or no potential for wildfire led to further restrictions on our dataset. Here, we eliminated observations from states that did not have wildfires ($n=6$) and re-ran the analysis using data only from states where wildfires have happened in the past 30 years ($n=42$). Results using this truncated dataset revealed sign and significance patterns identical to the analysis using the full dataset. Therefore, we only present results using the full results dataset. Another methodological concern is the interpretation of multiple t-tests. When multiple tests are run, the likelihood for a type one error increases (i.e., reporting a significant effect when there is none). Therefore, beyond simply relying on the t-test to compare values, we also provide the percent change which tells us about the magnitude of the differences. This gives the reader a chance to interpret whether the magnitude of difference is important from a practical perspective, irrespective of statistical strength. Finally, there may be spatial autocorrelation present in the social vulnerability variables. If this is the case, our standard errors may be artificially small and the statistical significance of our results may be inflated. Correcting for this using a spatial t-test would have required assuming the form of the spatial error matrix for each variable and within each region. We see no way to justify these assumptions. Therefore, we present the results of our t-test with added caution that statistical significance may be inflated.

4 Results

4.1 How do social vulnerability characteristics differ between areas with and without wildfire occurrence?

Testing for differences in mean values between census tracts with and without wildfire, we found statistically significant differences for all but one (people per housing unit) of the 26 social vulnerability variables (Table 5). Eighteen variables showed at least a 10% difference in their mean value (throughout the analyses, we consider 10% a meaningful difference), 13 of which indicated higher social vulnerability with wildfire occurrence. Thirteen of the 26 variables showed at least a 20% difference in their mean value, nine of which indicated higher social vulnerability with wildfire occurrence. Variables that showed

Table 5 Comparisons of social vulnerability variables between tracts that have experienced wildfire and those that have not

Social vulnerability pillar	Variable	Mean difference	t-stat	Mean wildfire	Mean non-wildfire	Percent difference (%)
Employment structure	Percent civilian unemployment	0.052	23.908***	0.301	0.250	20.72
	Percent employment in extractive industries	0.062	50.533***	0.094	0.032	193.55
	Percent employment in service industry	0.006	4.098***	0.181	0.175	3.55
	Percent female participation in labor force	−0.017	−11.413***	0.451	0.468	−3.73
Housing	Percent renters	−0.057	−17.007***	0.185	0.242	−23.39
	Percent mobile homes	0.105	39.255***	0.201	0.096	109.86
	Percent unoccupied housing units	0.093	35.636***	0.224	0.131	71.43
Population structure	Percent population under 5 years or 65 and over	0.020	12.585***	0.243	0.223	9.07
	Percent of children living in 2-parent families	0.023	5.696***	0.725	0.701	3.35
	Median age	2.466	13.505***	43.052	40.586	6.08
	Percent female	−0.015	−10.207***	0.485	0.500	−2.91
	Percent female-headed households	−0.017	−11.380***	0.096	0.113	−14.69
	People per unit	−0.006	−0.572	2.588	2.594	−0.23
Race/ethnicity	Percent Asian	−0.014	−12.334***	0.010	0.024	−57.31
	Percent Black	−0.037	−10.694***	0.051	0.088	−42.03
	Percent Hispanic	0.014	3.847***	0.117	0.103	13.22
	Percent Native American	0.024	18.895***	0.033	0.009	271.47
Socioeconomic status	Percent poverty	0.019	8.254***	0.159	0.140	13.33
	Percent households earning over $200,000 annually	−0.018	−11.594***	0.032	0.050	−36.10
	Per capita income	−4051.70	−13.613***	24,214.26	28,265.96	−14.33
	Percent with less than 12th grade education	0.026	12.934***	0.147	0.121	21.07

Table 5 (continued)

Social vulnerability pillar	Variable	Mean difference	t-stat	Mean wildfire	Mean non-wildfire	Percent difference (%)
Special needs	Percent households receiving social security benefits	0.052	21.223***	0.385	0.333	15.51
	Percent speaking English as a second language with limited English Proficiency	0.004	1.069	0.156	0.153	2.51
	Nursing home residents per capita	−0.002	−5.582***	0.004	0.005	−28.44
	Percent of population without health insurance	0.035	23.395***	0.138	0.103	33.59
	Percent of housing units with no car	−0.013	− 10.304	0.044	0.058	−23.22

Percent difference is the difference between wildfire and non-wildfire tracts

*$P <= .05$, **$P <= .01$, ***$P <= 0.001$

meaningful, higher social vulnerability with wildfire occurrence were distributed throughout five of the six pillars (all but population structure).

4.1.1 Employment structure

Two out of the four employment variables considered indicated meaningfully higher social vulnerability in wildfire tracts (Table 5): unemployment was 20% higher in wildfire tracts versus non-wildfire tracts and extractive industry employment was significantly higher in wildfire areas. While only 9% of the population works in extractive industries in wildfire tracts, this is nearly triple the percent working in extractive industries in non-wildfire tracts. Two additional variables showed statistically significant yet small differences between wildfire and non-wildfire tracts. These variables showed that a slightly lower percentage of females were employed in the labor force in tracts that experienced a wildfire (-4% difference) and a slightly higher percentage of the population (4% difference) were working in the service industry in wildfire tracts.

4.1.2 Housing

All three housing variables showed statistically significant and meaningful differences between wildfire and non-wildfire tracts; two of these indicated higher social vulnerability in wildfire tracts (Table 5). Unoccupied housing was nearly 9 percentage points higher in census tracts with wildfire compared to those without wildfire. Likewise, the percentage of people living in mobile homes in wildfire tracts (20%) was more than double the percentage in non-wildfire tracts (9.6%). On the other hand, the proportion of people living in renter-occupied households was 23% less in wildfire tracts.

4.1.3 Population structure

Population and household composition characteristics indicative of higher social vulnerability showed inconsistent relationships with wildfire exposure (Table 5). Only one variable, the percent of female-headed households, showed a meaningful difference. Relative to census tracts without wildfire, census tracts that experienced wildfire had lower proportions of female-headed households (−15%) and higher incidence of two-parent families (by 3%). Additionally, in wildfire tracts a lower percentage of the overall population was female. These variables are typically indicative of lower social vulnerability. However, wildfire tracts also had higher median ages (by 6%) and higher percentage of the population that were age dependent (by 9%), characteristics generally indicative of higher social vulnerability. There was no significant difference in the number of people per unit between wildfire and non-wildfire tracts.

4.1.4 Race and ethnicity

Wildfire occurrence was heterogeneously related to race and ethnicity characteristics (Table 5). The percent of the population that was Hispanic was 13% higher in tracts that experienced wildfire, while the percent that was Native American was 271% higher, although in each case the total percent in these categories was low in the tracts experiencing fire (11% and 3% of the total population, respectively). These characteristics are generally indicative of higher levels of social vulnerability in the USA. Conversely, census

tracts that experienced wildfire had lower Asian and Black populations relative to census tracts that did not experience wildfire. Both Asians and Blacks make up a small proportion of residents in census tracts in our study, and those tracts that experienced wildfire had on average 58% and 42% fewer Asian and Black individuals, respectively. These smaller proportions indicate relatively lower social vulnerability based on race and ethnicity.

4.1.5 Socioeconomic status

All four of the economic characteristics showed statistically significant and meaningful differences, indicating a clear pattern of higher wildfire exposure in places with higher levels of social vulnerability (Table 5). Per capita income was 14% lower in census tracts that experienced a wildfire, a difference of more than $4000 per person. A much smaller percentage of the population made more than $200,000 in the tracts that experienced fire. A larger proportion (by 13%) of people lived in poverty in wildfire tracts. Likewise, a larger proportion (by 21%) of people in wildfire census tracts had less than a 12th grade education.

4.1.6 Special needs

Wildfire occurrence was heterogeneously related to special needs. Four of the five variables in this pillar showed meaningful and significant differences between wildfire and non-wildfire tracts but with differing implications for social vulnerability (Table 5). The percentage of uninsured people (healthcare) in the wildfire tracts was nearly 34% higher than in non-wildfire tracts, and a larger proportion of households (by 15%) received social security benefits compared to tracts that had not experienced a wildfire. Both of these characteristics are equated with higher social vulnerability levels. However, in wildfire tracts, a smaller proportion of the population (by 28%) lived in nursing homes and households were more likely to have a car (by 23%). These characteristics would indicate lower social vulnerability. Comparing wildfire and non-wildfire tracts, there was no significant difference in English language proficiency among residents who spoke English as a second language.

4.2 Are these differences in social vulnerability characteristics between burned and unburned areas consistent across regions?

Results of the regional scale analyses were similar to the nationwide pattern (Table SI1). Out of 208 total results (8 regions × 26 variables), 163 (or 78%) had the same corresponding sign and significance level when compared to the national level result. Only 13 observations (6%) differed in both sign and significance. Forty observations (19%) differed in significance, but not sign.

Generally, the magnitude of differences was also similar except for Hispanic population, percent of people with limited English proficiency, the proportion of people with less than 12th grade education, and service industry employment, which displayed more heterogeneity across regions (Fig. 2). Only the Northwest region shows a greater proportion of Hispanic residents in wildfire tracts (15% vs. 11% in non-wildfire tracts), matching the direction of the US pattern (Fig. 2). California and the Interior West show fewer Hispanic residents in wildfire tracts compared to non-wildfire tracts (22% vs. 31% in California, and 15% vs. 21% in Interior West). Differences in the Hispanic

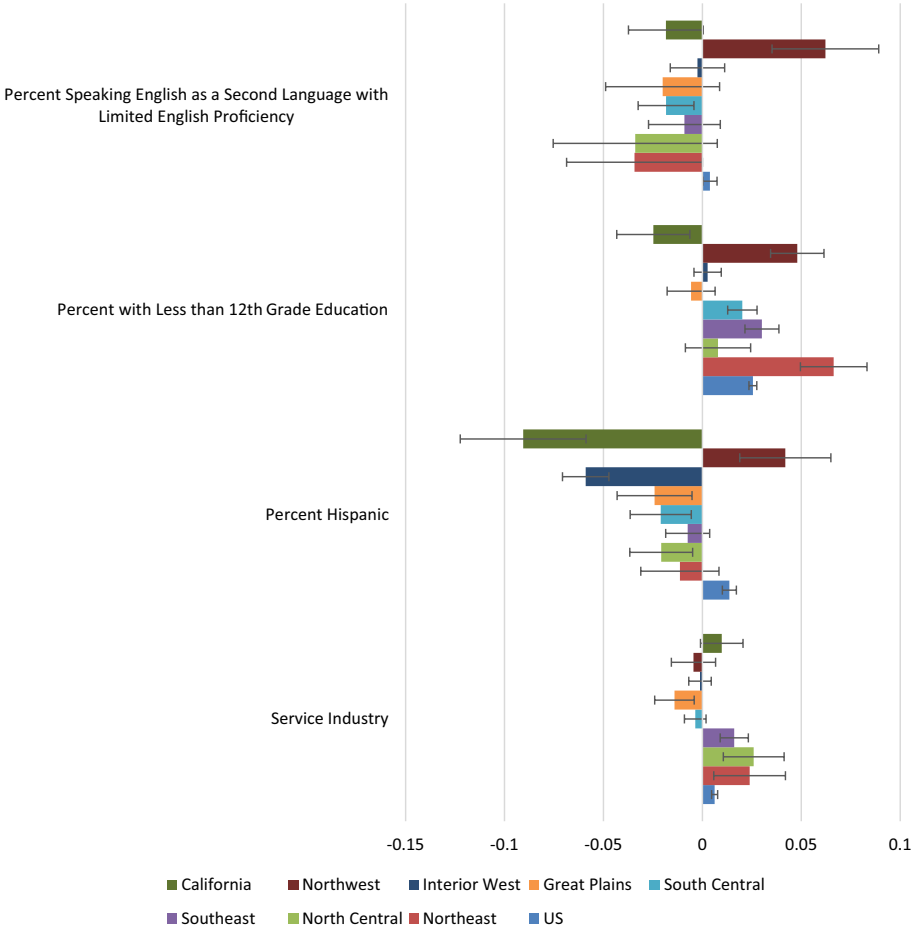

Fig. 2 Colored bars show the difference between the mean value of each social vulnerability variable in wildfire (burned) and non-wildfire (unburned) census tracts within the USA and eight USDA Forest Service assessment regions. Whiskers show the standard error of the mean

population in these regions are statistically significant and meaningful. Furthermore, only in the Northwest is the percent of people with limited English proficiency significantly and meaningfully greater in wildfire tracts (24% vs. 17% in non-wildfire tracts). This matches the direction of the US pattern but differs from all other regions (Fig. 2). California defies the trend observed in other regions when considering the percent of people with less than a 12th grade education living in wildfire tracts (Fig. 2). Only in California are there proportionally *fewer* people with lower educational attainment in wildfire tracts (12% vs. 15% in non-wildfire tracts). In other words, California is unique because tracts with meaningfully higher educational attainment experienced greater wildfire occurrence. Finally, the Great Plains differs from other regions because tracts where wildfire had occurred showed slightly lower service sector employment; this relationship is statistically significant but small (Fig. 2).

4.3 Are these differences in social vulnerability characteristics between burned and unburned areas consistent for low WUI and high WUI census tracts?

Relationships between social vulnerability indicators and wildfire experience more closely mirrored nationwide patterns in high WUI tracts ($n = 816$) than in low WUI tracts ($n = 152$) (Tables 5, 6). Poverty was the only variable where high WUI tracts differed in any way from the national result: while high WUI tracts with wildfire occurrence also showed a higher proportion of people living in poverty than non-fire tracts, this difference was too small to be deemed meaningful (less than 10% difference). Otherwise, sign and significance patterns of all 26 social vulnerability variables in high WUI tracts matched national results, although the magnitude of these differences tended to be smaller than the magnitude of differences observed nationally.

For low WUI tracts, when we compared tracts with and without wildfire occurrence, we found nine social vulnerability variables where the sign and/or significance differed from the national comparison of tracts with and without wildfires. An additional three variables that matched the sign and significance pattern in the national result showed meaningful differences between burned and unburned tracts only in low WUI areas. These twelve departures from the national result were observed across four of the six social vulnerability pillars: employment structure, population structure, socioeconomic status, and special needs.

Compared to the national result, three employment variables in low WUI tracts showed differences in their relationships with wildfire (Tables 5, 6). Service sector employment and proportion of females in the labor force were both significantly lower in rural tracts that had burned. Unemployment in these low WUI tracts proved neither statistically significant nor meaningful in its association with wildfire occurrence. Five of six population structure variables in low WUI tracts diverged from the national trend when comparing tracts with wildfire and those without (Tables 5, 6). Percent female was meaningfully lower in low WUI tracts that had burned (in contrast, in high WUI tracts and for national results the same comparison did not find a meaningful difference). The median age and proportion of children in two-parent households were both lower in wildfire tracts, but not a meaningful (10% or greater) difference. The number of people per unit showed a significant difference: On average, there were slightly fewer people per unit in low WUI wildfire areas. Finally, age dependence did not show a statistically significant relationship with wildfire, whereas for high WUI and national results there was a statistically significant, positive (but not meaningful) association with wildfire. Poverty was the only socioeconomic variable that differed from the national pattern. The difference in the rate of poverty was not significant between low WUI tracts that had burned and those that did not. Finally, three variables from the special needs pillar diverged from the national pattern. The proportions of social security beneficiaries and of nursing home residents showed no significant differences between wildfire tracts and non-wildfire tracts in low WUI areas. The limited English proficiency population was meaningfully higher in low WUI wildfire tracts; however, the variable fell beyond the threshold for statistical significance.

Table 6 Comparisons of social vulnerability variables between tracts that have experienced wildfire and those that have not for high WUI and low WUI tracts

Social vulnerability pillar	Variable	High WUI Tracts ($n=816$)				Low WUI Tracts ($n=152$)			
		t-stat	Mean wildfire	Mean non-wildfire	Percent difference (%)	t-stat	Mean wildfire	Mean non-wildfire	Percent difference (%)
Employment structure	Percent civilian unemployment	14.471***	0.308	0.260	18.80	−1.402	0.215	0.227	−5.23
	Percent employment in extractive industries	17.740***	0.048	0.022	117.19	19.318***	0.135	0.035	282.68
	Percent employment in service industry	3.778***	0.192	0.182	5.36	−2.942**	0.153	0.171	−10.60
	Percent female participation in labor force	−6.545***	0.462	0.475	−2.78	−10.076***	0.384	0.461	−16.77
Housing	Percent renters	−7.731***	0.196	0.238	−17.59	−5.244***	0.203	0.277	−26.80
	Percent mobile homes	17.816***	0.187	0.101	84.67	11.814***	0.140	0.054	157.25
	Percent unoccupied housing units	16.676***	0.221	0.141	57.03	4.435***	0.141	0.105	34.25
Population structure	Percent population under 5 years or 65 and over	6.809***	0.247	0.228	8.62	−1.705	0.203	0.214	−5.08
	Percent of children living in 2-parent families	2.849***	0.725	0.707	2.63	−2.447*	0.637	0.680	−6.37
	Median age	7.118***	43.697	41.566	5.13	−4.215***	35.268	38.502	−8.40
	Percent female	−6.711***	0.494	0.506	−2.23	−9.469***	0.422	0.493	−14.48
	Percent female-headed households	−6.020***	0.101	0.115	−12.18	−5.878***	0.078	0.114	−31.55
	People per unit	−0.632	2.612	2.622	−0.37	−3.351***	2.370	2.542	−6.77
Race/ethnicity	Percent Asian	−5.308***	0.016	0.027	−41.35	−3.981***	0.009	0.027	−65.29
	Percent Black	−5.831***	0.052	0.084	−38.47	−3.531***	0.037	0.083	−54.89
	Percent Hispanic	2.255*	0.121	0.108	12.14	3.607***	0.177	0.121	45.37
	Percent native American	4.466***	0.018	0.009	92.57	11.358***	0.028	0.005	486.33

Table 6 (continued)

Social vulnerability pillar	Variable	High WUI Tracts ($n=816$)				Low WUI Tracts ($n=152$)			
		t-stat	Mean wildfire	Mean non-wildfire	Percent difference (%)	t-stat	Mean wildfire	Mean non-wildfire	Percent difference (%)
Socioeconomic status	Percent poverty	3.648***	0.152	0.139	9.67	0.263	0.143	0.140	1.77
	Percent households earning over $200,000 annually	−5.811***	0.042	0.059	−29.24	−4.133***	0.024	0.046	−48.84
	Per capita income	−6.180***	26,494.74	29,734.00	−10.89	−6.403***	20,071.550	27,817.730	−27.85
	Percent with less than 12th grade education	6.708***	0.134	0.114	17.98	3.168**	0.146	0.120	21.97
Special needs	Percent households receiving social security benefits	10.806***	0.388	0.342	13.48	−0.717	0.298	0.305	−2.18
	Percent speaking English as a second language with limited English proficiency	0.059	0.144	0.144	0.23	1.556	0.184	0.163	12.80
	Nursing home residents per capita	−3.880***	0.003	0.005	−33.79	0.823	0.007	0.006	15.61
	Percent of population without health insurance	10.630***	0.127	0.102	24.29	5.315***	0.130	0.099	32.07
	Percent of housing units with no car	−4.774***	0.046	0.055	−16.64	−4.678***	0.037	0.066	−44.16

Percent difference is the difference between wildfire and non-wildfire tracts

*$P <= .05$, **$P <= .01$, ***$P <= 0.001$

5 Discussion

Patterns of increasing wildfire occurrence and losses in the USA invite questions about how social vulnerability may be related. Our nationwide analysis considered a wide range of potential aspects of social vulnerability and found that when there were differences in demographic characteristics with respect to wildfire exposure, it was the places that experienced wildfire that also generally had higher social vulnerability. As one of the first studies to examine wildfire exposure and a broad conception of social vulnerability nationwide, our finding of higher social vulnerability in places where wildfire has occurred diverges from the pattern of generally lower social vulnerability found in areas with high wildfire hazard potential (e.g., Davies et al. 2018; Wigtil et al. 2016). Put simply, answering the question "who *has* experienced wildfire?" tells a different story than "who *could* experience wildfire?".

Our use of 26 distinct measures enabled us to identify unique attributes of wildfire and social vulnerability and consider how those factors intersect. Using individual variables, beyond simple higher/lower social vulnerability indices or scores, is helpful in uncovering how social vulnerability may be expressed or realized when fires occur. For example, at the national scale, we found consistent socioeconomic differences between places that had experienced wildfire and those that had not. These socioeconomic differences combined with employment structure and aspects of special needs dimensions. Per capita income in tracts that experienced wildfires was nearly $4000 lower than in tracts that did not experience wildfire. Lower incomes were coupled with, on average, nearly 20% higher unemployment, a 13% higher poverty rate, and a 21% higher rate of residents with less than a 12th grade education. Further, we found wildfire tracts had larger concentrations of employment in extractive industries, which may be more vulnerable to disruption when wildfires occur (see Mendez et al. 2020). Populations were also more likely to be older and age-dependent—groups that require special consideration for evacuation and smoke mitigation. Wildfire tracts contained higher proportions of social security recipients and a higher percentage of residents lacking health insurance. Socioeconomic differences were also reflected in housing: mobile homes comprised more than 20% of housing in wildfire tracts, compared to only 10% in non-wildfire tracts. On average, 22% of homes in wildfire tracts were vacant. Among population characteristics, Native American populations were more than three times as high in wildfire tracts than non-wildfire tracts.

Findings from the present study cast new light on national studies which typically conclude that populations at highest biophysical risk of wildfire are more privileged. Those previous findings may reflect narrower datasets used that measured wildfire hazard potential (Davis 2018, Wigtil 2016). For example, only a very small portion of US Census tracts are designated as highest biophysical risk (e.g., only 2% of tracts in Davies et al. 2018), which excludes many of the places in the US that regularly experience wildfire. Furthermore, with the exception of one regional study (Anderson and Sugg 2019), studies that focus on wildfire hazard potential tend to consider biophysical risk as a point-in-time snapshot rather than using multiple observational periods. Our major finding, of higher social vulnerability in places with wildfire, agrees with previous studies, both national and regional, that consider some degree of wildfire exposure over time (e.g., Grala et al. 2017; Masri et al. 2021; Rappold et al. 2017).

Our study design also allowed us to examine variation in subnational trends, comparing regional patterns and locations with different levels of WUI development. While regional patterns were generally consistent with the national trend, several regions displayed

nuances in their social vulnerability profile with respect to wildfire. In the Pacific Northwest, a higher proportion of Hispanic residents live in wildfire tracts, whereas in six other regions (all except the Southeast) wildfire tracts contain significantly smaller Hispanic populations. Furthermore, wildfire areas in the Northwest show an intersection with higher levels of language vulnerability. Additionally, only in California do people in wildfire tracts possess significantly higher levels of education; wildfire tracts in other regions contain populations with, on average, lower levels of education. Such a pattern suggests that affluence may coincide with wildfire occurrence in California (Erikson and Simon 2017). Considering the myriad case studies about California fires, this pattern may also fuel unsafe assumptions that people in wildfire areas are less vulnerable overall nationwide, which our results show not to be the case. Moreover, even within relatively more affluent tracts, it is important to acknowledge that social vulnerability can vary widely at finer spatial scales (Collins 2005).

Similar to the regional level deviation from national trends, we found only subtle differences in social vulnerability when comparing high WUI and low WUI (rural) tracts based on wildfire occurrence. Generally, relationships between wildfire and aspects of social vulnerability were consistent when we compared national trends and only high WUI areas. Wildfire tracts classified as high WUI showed higher proportions of Social Security beneficiaries and lower proportions of nursing home residents, yet neither measure differed with wildfire presence in low WUI (rural) tracts. Low WUI (rural) tracts having experienced wildfire were distinguished by their lack of gender diversity (significantly fewer females and female-headed households), lower average incomes (but not higher poverty rates), higher proportion of Hispanic residents, and meaningfully but not universally higher language vulnerability. Given the extent of wildfire losses in rural areas (Kramer et al. 2018), our study suggests it may be worth further exploring how vulnerabilities are uniquely expressed in rural areas, beyond the set of variables considered here.

5.1 Management implications of social vulnerability to wildfires

It is beyond the scope of this study to examine how these differences in demographic characteristics with wildfire exposure have emerged, be they the result of larger societal and economic forces, natural resource policy, or post-wildfire population changes. We note, however, that regardless of the root and proximate causes of the observed demographic patterns, it is concerning that people in tracts that have experienced wildfire possess lower social vulnerability. Additionally, these very places that have experienced wildfire in the past are likely to burn again.

Our findings suggest several ways in which residents of areas that have burned in the past may have lower capacity to prevent future ignitions or mitigate wildfire impacts. Places that have experienced wildfire tend to be more economically vulnerable: they contain higher rates of poverty, lower levels of educational attainment, higher employment in extractive industries, higher proportions of social security recipients, and a higher percentage of residents lacking health insurance. This combination of factors suggests that residents may have fewer options to pay for wildfire risk reduction on their own property (e.g., home hardening, vegetation removal) and may have fewer financial safety nets to recover successfully when wildfire does occur. Economically vulnerable residents are likely to struggle with medical bills, where injuries or worsened chronic conditions result from fire, and with housing replacement costs (Rizza et al. 2012; Liu et al. 2015; Grant and Runkle

2022). Accessing aid following wildfires may also be difficult due to low levels of literacy (James et al. 2007).

Places that have experienced wildfires also tend to be more age dependent (i.e., they have higher proportions of residents over age 65 and under age 5), meaning residents may be more physically vulnerable. The median age skews older, yet fewer residents live in nursing homes compared to non-burned areas suggesting that burned areas may have a larger share of elderly people living independently. Since disabilities and chronic conditions increase with age, older adults may take longer to evacuate, especially when living alone (Fu et al. 2022). In multi-person households, the presence of an aged household member may reduce the speed at which the entire household evacuates (Iezzoni et al. 2001; Toledo et al. 2018; Wu et al. 2022). Furthermore, older adults with chronic conditions living on fixed incomes face a combination of physical and economic vulnerability. While they tend to be reliant on specialized assistive devices (e.g., hearing aids, eyeglasses, CPAP machines), their capacity to replace devices damaged in a wildfire or lost during evacuation is limited (Backer et al. 2023; Zybach et al. 2009). Economic and physical vulnerabilities make it more difficult to secure affordable and accessible housing if a large proportion of the housing stock has burned (Lee and Li 2021; Lee et al. 2022; Duprey et al. 2021).

In terms of housing vulnerability, higher proportions of mobile home residents and lower proportions of renters in areas that have experienced wildfire suggest high variability among households in the capacity to recover from wildfire and to mitigate future risks. On the one hand, homeowners, representing a larger share of households in wildfire areas, have greater access to recovery resources (e.g., Federal Emergency Management Agency housing assistance, Small Business Administration loans, homeowner's insurance) and more control than renters over their properties (Lee and Van Zandt 2019). However, the significant proportion of vacant properties in wildfire tracts suggests a high degree of seasonally occupied second homes; this could exacerbate wildfire exposure among neighboring properties as previous research indicates that part-time homeowners are less likely to invest time in risk reduction efforts such as vegetation maintenance (Bright and Burtz 2006; Brenkert-Smith 2010). Mobile homes in wildfire prone areas are of concern because they are often challenging to insure and tend to be more susceptible to wildfire based on materials (Johnson Gaither et al. 2011; Chase and Hansen 2021). Replacing and reinsuring mobile homes may be complicated by issues of divided-tenure (i.e., where residents own the mobile home but not the land beneath), communal ownership (i.e., heirship properties), lack of insurance, and/or stigma associated with affordable housing (Dyer and Bailey 2008; Rumbach et al. 2020; Chase and Hansen 2021). Furthermore, older mobile homes, especially those manufactured before 1976, may be more likely to have been purchased as chattel property, meaning their value depreciates over time like an automobile, rather than increasing; the combination of a mobile home purchased as chattel property and its location on heirship property could limit the availability of homeowner's insurance and lessen the resources available to recover after a wildfire loss (Johnson et al. 2020).

Livelihood and language vulnerabilities are also present in some areas that have experienced wildfire. On average, these places include larger concentrations of Native Americans and slightly higher concentrations of Hispanic residents. In the Northwest region, these characteristics coincide with a high proportion of non-English speakers. Even in places with smaller concentrations of Latino residents and non-English speakers, there is recognition of the need for disaster information in Spanish and other local languages. For example, state auditors in California determined that enhancing emergency response information for non-English speakers was a critical need after the 2017 wildfire season (State of California 2019). Higher incidence of Hispanic residents, coupled with the higher employment in

extractive industries in wildfire tracts, points to agricultural work that may be threatened by recurrent fires. Migrant and seasonal farm workers may be especially mobile, less connected to local social support networks, and thus, overlooked by emergency planners (Mendez et al. 2020; Montz et al. 2011). Furthermore, farm workers who are undocumented do not qualify for government disaster assistance and tend to be reluctant to seek formal aid for injuries or losses (Gares and Montz 2014; Mendez et al. 2020). Native Americans who work in natural resource industries or who are dependent on subsistence livelihoods could also be disproportionately impacted by conversion of tree cover to grasses, soil erosion, sedimentation, and other water quality issues associated with wildfire. Moreover, impacts to flora and fauna from wildfires that are more frequent or intense than a region's natural fire regime allows may threaten keystone species, limit traditional land management practices (e.g., cultural burning), and imperil collective cultural identity (Long and Lake 2018).

Finally, gender disparities found in rural areas that have experienced wildfire may have implications for psychological vulnerability after fire. Rural wildfire tracts in our study displayed meaningfully lower proportions of females and working females and consequently more males both present and in the labor force. Although these indicators are typically equated with lower social vulnerability, such an interpretation may be too simplistic (Enarson and Morrow 1998). Instead, research suggests that culturally specific gender norms make men differently vulnerable to disaster-induced trauma as notions about masculinity, familial roles, and mental health may inhibit help-seeking behaviors and lead to male isolation, addiction behaviors, or increased domestic violence (Saito 2014; Nummi and Henderson 2017; Parkinson 2019).

5.2 Policy relevance of social vulnerability to wildfires

These patterns of association between various aspects of social vulnerability and wildfire occurrence also suggest ways in which entities addressing wildfire threats will need to consider local capacity to undertake wildfire adaptation and preparation efforts. Locations and residents facing persistent social challenges may be less readily served by grant or assistance programs where equity is not a central concern. For example, in the Southeast, Johnson Gaither et al. (2011) found longer mean distances between "hot spot" communities (i.e., those with both higher-than-average wildfire risk and social vulnerability) and Community Wildfire Protection Plans/Firewise locations.

Consequently, federal programs are beginning to consider aspects of social vulnerability in the design and administration of government programs. For example, a broad executive order (Executive Order 14,008, 2021) announced Justice40, which mandates that at least 40% of the benefits of selected federal programs must flow to disadvantaged communities. These programs include the Federal Emergency Management Authority's (FEMA) Building Resilient Infrastructure and Communities (BRIC) and Flood Mitigation Assistance (FMA) programs. FEMA's recent "Building Cultures of Preparedness" report (FEMA 2019), which underscores the importance of understanding local social context and leveraging existing community capacity, further illustrates the inclusion of social vulnerability in the agency's disaster education, prevention, and assistance programs. Specific efforts to confront wildfire risk are also considering social vulnerability or underserved communities. For example, the 2021 Infrastructure Investment and Jobs Act program created a new grant program (Community Defense Wildfire Grants) to help at-risk local communities and tribes reduce wildfire risk; the program specifically prioritizes low-income and/or underserved communities and waives match requirements (USDA 2023). Beyond assistance to

communities, efforts to model physical wildfire risk are also incorporating social characteristics of those communities and residents to further prioritize places where the most vulnerable residents are facing wildfire threats (USDA 2022).

Prioritizing underserved communities in program design and delivery at multiple scales poses some challenges. Many of these social vulnerability measurements are being used at the county-level to provide nationally standardized information in a format that is easily accessible for communities and local governments to draw upon, but as we have demonstrated, one composite index may either elide key vulnerabilities or include variables that do not appear, from our study, to be related to wildfire exposure (e.g., car ownership, homeownership). We also note that counties are often large and diverse and there can be scale mismatches between county-level data and vulnerable populations. For instance, in California, Los Angeles County may have a lower overall social vulnerability composite score, but the high wildfire risk concentrated in the Santa Monica Mountains most directly affects a wealthier population. Other counties that show lower social vulnerability overall, such as Ventura or Santa Barbara Counties, can still be home to substantial concentrations of more vulnerable residents (Mendez et al. 2020). Ultimately, demonstrating and enhancing the efficacy of community assistance and wildfire harm reduction programs for vulnerable populations necessitates going beyond indices created with secondary data alone. Such efforts will likely require targeted engagement with socially vulnerable residents themselves and the local organizations who support their specialized needs in adapting to chronic wildfire threats.

5.3 Limitations

Despite our efforts to be systematic and comprehensive in considering the intersections of wildfire exposure and social vulnerability, several limitations exist in our data and analysis techniques. First, given the unequal size of census tracts and variation in wildfire size and frequency over time, we chose to keep our measure of exposure consistent and denote only presence or absence of wildfire over time in tracts. We accounted for neither wildfire frequency (number of recurrent fires) nor measures of wildfire impacts (e.g., proportion of area burned, severity or duration of wildfire events). This approach was well suited for revealing locations where *any* exposure between socially vulnerable populations and wildfire occurred, and it likely contributed to findings that were consistent over regions and across WUI and rural areas. In future studies, consideration of frequency and wildfire severity will be helpful in further exploring how different areas and populations are experiencing wildfire. For example, Masri et al (2021) found that in California wildfire frequency and extent (proportion of impacted area) had different relationships with social vulnerability.

A second limitation, acknowledged earlier, is that we used a static SOVI measurement (2006–10) and did not reconstruct SOVI based on the social data collection nearest in time to each fire. While this methodological choice prevented any inconsistencies that would have been introduced by constructing SOVI variables from multiple data sources across our study period (1984–2018), the timing of our social vulnerability data pull relative to timing of each fire begs a follow-up question about causality that is beyond the scope here: to what extent were these fires products of or producers of sensitivity to wildfire? Given that our study is the first, to our knowledge, to systematically explore spatial relationships between social vulnerability and previous wildfire occurrence nationwide (Table 1), we maintain the appropriateness of this simplification; however, we acknowledge the need for

future studies to account for the dynamism of social vulnerability and interactions between multiple characteristics across spatial scales. Future studies could also, for example, utilize more intensive statistical 'difference-in-difference' techniques that assess the outcomes of wildfire preparedness or recovery programs on specific vulnerable groups.

Finally, like many of these studies, we are dependent upon nationally available, consistent data at the tract level, which has some inherent limitations. ACS data in more rural areas will be potentially constrained by smaller sample sizes and hard-to-count populations (e.g., immigrant populations, seasonal residents, limited English speakers). Finally, census tracts in rural areas can be large, holding a wide variation in housing forms and population characteristics, which may not be reflected in summary measures such as median income or proportion of WUI housing (Collins 2005; Champ et al. 2022).

6 Conclusion

Using a suite of 26 social variables, this study makes a novel contribution to the growing scholarship on wildfire risk and socially vulnerable populations by addressing the question of "who *has* burned over the past several decades in the US?" rather than "who *could* burn?". Overall, we find that census tracts that have experienced wildfire exhibit social vulnerability characteristics different from places that have not. This result is robust across regions and when WUI and rural areas are compared. This finding suggests that the limited capacity of these areas to reduce their own wildfire risk may have contributed to their exposure. Furthermore, their vulnerability may hinder their future ability to prepare for and respond to similar events. Nevertheless, the analysis and findings presented here illuminate the potential for social vulnerability indicators to help policy makers and leaders more meaningfully direct funding, target resources, and tailor interventions for a future in which we must learn to live with fire.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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